5.0 MODELING

SECTION 5.0, MODELING

INSERT BEFORE PAGE 5-1

NOTE ON NAMES OF REQUESTED INJECTION INTERVALS

Throughout Section 5.0 and all of its tables, figures, and appendices, all instances of "Lower Frio" refer to the Lower Frio injection interval, and all instances of "Upper Frio" refer to the Upper and Middle Frio injection interval.

5.0 MODELING

This section will address the effects of injection into WDW-157, WDW-169, WDW-249, and the proposed WDW-407 and WDW-422, in addition to injection into nearby Class I and Class II wells, on the pressure in the reservoir and the waste plume configuration following a 10,000-year post-operational migration period. Section 5.1 addresses the pressure at the wellbore and in the reservoir, Section 5.2 addresses the lateral migration of the waste plume, and Section 5.3 addresses the vertical migration of the plume. State agency information pertaining to injection volumes for wells at the Texas Molecular and Vopak sites are contained in Appendix 5.0-1. The original (2007) submittal included four Class I and three Class II wells located near the Vopak and TMDPS sites. This submittal (2015) includes additional Class I and Class II wells in response to questions from EPA. A total of eleven (11) nearby Class I wells and four (4) Class II wells are included in this submittal. The injection volumes for the two Vopak wells, three Texas Molecular wells, eleven nearby Class I wells, and four Class II wells has been addressed in the pressure and plume modeling. Injection volumes for these nearby wells are contained in Attachment B. The Class II offset wells used in the reservoir modeling have been discussed in Section 3.7.6. The location of the wells used in the 2007 pressure and plume models are presented in Table 5.0-I. The locations of the wells used in the additional (2015) modeling are presented in Table 5.0-II.

5.1 Reservoir Pressure Buildup

5.1.1 Objectives

The primary objective of pressure modeling is to establish the location of the COI for the site at the end of the operational period and wellbore pressures during the operational period. It is desirable to utilize reservoir rock properties and fluid properties which will result in calculated pressures which are conservative, i.e., higher, when compared to actual pressure measurements. The formation porosity, reservoir brine viscosity, and total compressibility have been discussed in Section 3.0 and exhibit either limited or no variation.

The 2007 submittal considered two reservoir configurations which included injection from four nearby Class I and three Class II wells:

1. Infinite acting reservoir.
2. Reservoir containing a single no-flow boundary located 3,000 feet NNW of WDW-157 and 5,000 feet NNW of WDW-169 and oriented WSW to ENE.

For this submittal (2015) a new strategy was developed to complement the previous pressure modeling. All known Class I and Class II wells within ten miles of Vopak's and Texas Molecular's facilities have been included in this modeling. Four faults have been implemented. The pressure modeling considers the faults to have varying degrees of transmissivities. The cases considered for fault transmissiveness were fully sealing (0% transmissive), partially transmissive (25%, 50%, 75%, 90%, and 95%), and infinite acting (100% transmissive).

Table 3.1-I includes the rock and fluid properties used in the calculation of reservoir pressure buildup.

5.1.2 Modeling Historical Pressure

The average monthly injection rates for all wells since injection began in June 1969 (Equistar WDW-36) through December 2014, have been utilized in modeling the historical pressure at the WDW-157, WDW-169, and WDW-249 wellbores. In order to obtain a more accurate comparison of pressures measured during annual testing, the actual rates and durations during the month prior to the testing were utilized for WDW-157, WDW-169, and WDW-249. Tables 5.1.2-I through 5.1.2-III list the historical rates used for WDW-157, WDW-169, and WDW-249. Table 5.1.2-IV lists the rates used in the nearby Class I and Class II wells.

2007 Modeling

Tables 5.1.2-V through 5.1.2-VII show measured flowing and shutin pressures in addition to the modeled pressures for WDW-157, WDW-169, and WDW-249. Figures 5.1.2-1 through 5.1.2-3 show the modeled historical wellbore pressure at WDW-157, WDW-169, and WDW-249. The measured annual shutin pressure and estimated flowing pressure at the time of annual testing are also shown. The measured flowing pressures were derived from the flowing pressure prior to the start of the falloff tests and have been adjusted for the effects of near wellbore skin damage. A summary of the well test information is provided in Tables 3.2.4-I through 3.2.4-III. A permeability of 120 md and reservoir thickness of 142 feet were determined to provide simulated pressures which were conservative (i.e., higher) when compared to measured pressures when considering an infinite acting reservoir. For the case of a reservoir with a single fault, a permeability of 300 md and thickness of 142 feet yield conservative results. Appendix 5.1.2-1 contains the PredictW input and output for the modeled flowing pressures in an infinite acting reservoir during the historical period. Appendix 5.1.2-2 contains the PredictW input and output for the case of a reservoir with a single fault.

2015 Modeling Addition

Tables 5.1.2-VIII through 5.1.2-X show the measured flowing and shut-in pressures for WDW-157, WDW-169, and WDW-249 in addition to the modeled wellbore pressure for the partially transmissive fault cases. A permeability of 625 md and reservoir thickness of 142 feet were utilized for these model runs. Figures 5.1.2-4 through 5.1.2-6 show the modeled historical wellbore pressure increase at WDW-157, WDW-169, and WDW-249 compared to the measured values. Appendix 5.1.2-3 contains the PredictW input and output for these modeling runs.

5.1.3 Wellbore Pressure Rise During Operational Life and Pressure Decline After Shutin

2007 Modeling

The reservoir pressure modeling for the Lower Frio presented in the 2007 submittal was based on the following rate schedule:

Well	Rate (gpm)	Time Period
WDW-157	300	01/01/2007 – 12/31/2017
WDW-169	225	01/01/2007 – 12/31/2017
WDW-249	225	01/01/2007 – 12/31/2017
WDW-407	150	01/01/2007 – 12/31/2017

The reservoir pressure rise in the Upper Frio is based on an injection rate(s) not to exceed a total of 175 gpm into the Upper Frio. Both the Vopak and Texas Molecular sites will each have a total of 730 days during the period between January 1, 2007 and December 31, 2017 to inject into the Upper Frio.

Since several scenarios are possible when the use of the Upper Frio becomes necessary due to a mechanical failure in the Lower Frio completion of a well, the modeling of reservoir pressure buildup will be limited to the scenarios which will maximize pressure buildup. Injection into the Upper Frio occurred previously for approximately one year during the period of November 1999 through October 2000. Pressure buildup will be maximized if injection is modeled to begin at the start of the future injection period, which starts January 1, 2007. Pressure buildup will also be maximized if two wells utilize the Upper Frio "back to back" rather than years between use. One scenario would be 730 days injection into WDW-157 followed by 730 days injection into WDW-169. Eight combinations are possible if each site only uses one well for a two-year period.

Lower Frio

Infinite Acting Reservoir

Figures 5.1.3-1 through 5.1.3-4 show the projected bottom-hole flowing and annual 24-hour shutin pressures versus time at the top of Sand 1 in WDW-157, WDW-169, WDW-249, and WDW-407 for the infinite acting reservoir case. The projected maximum pressures on December 31, 2017, at the top of the Lower Frio are presented in the following table:

Well	Modeled Wellbore Pressure on December 31, 2017 (psia)	Increase Over Original Pressure (psi)
WDW-157	3881.26	889.22
WDW-169	3818.39	830.50
WDW-249	3812.25	823.90
WDW-407	3746.77	754.73

Tables 5.1.3-I through 5.1.3-IV list the projected flowing and annual 24-hour shutin pressures at the top of Sand 1 for WDW-157, WDW-169, WDW-249 and WDW-407.

Figures 5.1.3-5 through 5.1.3-8 depict the decline in pressure at the wells for a one-year period following shutin. Wellbore pressures will decline below the critical pressure rise of 248.48 psi within 156 to 161 days of shut-in, depending on the well.

The PredictW input data and output results for 11 years of continuous injection, followed by a one-year shutin, are presented in Appendix 5.1.3-1. Appendix 5.1.3-2 contains the PredictW input and output for the annual 24-hour shutin periods.

Reservoir with Single Fault

Figures 5.1.3-9 through 5.1.3-12 show the projected bottom-hole flowing and 24-hour shutin pressure versus time at the top of Sand 1 in WDW-157, WDW-169, WDW-249 and WDW-407 for the case of a reservoir with a single fault. The projected maximum pressures on December 31, 2017, at the top of the Lower Frio are presented in the following table:

Well	Modeled Wellbore Pressure on December 31, 2017 (psia)	Increase Over Original Pressure (psi)
WDW-157	3526.07	534.03
WDW-169	3485.74	497.85
WDW-249	3482.15	493.80
WDW-407	3473.8	481.76

Tables 5.1.3-I through 5.1.3-IV list the predicted flowing and annual 24-hour shutin pressures at the top of Sand 1 for WDW-157, WDW-169, WDW-249 and WDW-407.

Figures 5.1.3-13 through 5.1.3-16 depict the decline in pressure at the wells for a one-year period following shutin. The pressure at the wellbore will decline below the critical pressure within 38 to 40 days of shut-in, depending on the well.

The PredictW input and output results for 11 years of continuous injection, followed by a one-year shutin, are presented in Appendix 5.1.3-3. Appendix 5.1.3-4 contains the PredictW input and output for the 24-hour annual shutins.

Upper Frio

Infinite Acting Reservoir

Figures 5.1.3-17 through 5.1.3-20 show the projected bottom-hole flowing and annual 24-hour shut-in pressures versus time at the top of the Upper Frio injection interval sands in WDW-157, WDW-169, WDW-249, and WDW-407 for the infinite acting reservoir case. The projected maximum pressures on December 31, 2017, at the top of the Upper Frio are presented in the following table:

Well	Modeled Wellbore Pressure on December 31, 2017 (psia)	Increase Over Original Pressure (psi)
WDW-157	3156.72	784.34
WDW-169	3166.63	794.25
WDW-249	3169.85	794.25
WDW-407	3156.72	784.34

Tables 5.1.3-V through 5.1.3-VIII list the projected flowing and annual 24-hour shut-in pressures at the top of the Upper Frio injection interval sands for WDW-157, WDW-169, WDW-249 and WDW-407.

Figures 5.1.3-21 through 5.1.3-24 depict the decline in pressure at the wells for a one-year period following shut-in. Wellbore pressures will decline below the critical pressure rise of 230.22 psi within 1.5 days of shutin.

The PredictW input data and output results for 4 years of injection (2 years at offset well followed by 2 years at well in question), followed by a one-year shut-in, are presented in Appendix 5.1.3-5. Appendix 5.1.3-6 contains the PredictW input and output for the annual 24-hour shut-in periods.

Reservoir with Single Fault

Figures 5.1.3-25 through 5.1.3-28 show the projected bottom-hole flowing and 24-hour shut-in pressure versus time at the top of the Upper Frio injection interval sands in WDW-157, WDW-169, WDW-249 and WDW-407 for the case of a reservoir with a single fault. The projected maximum pressures on December 31, 2017, at the top of the Upper Frio are presented in the following table:

Well	Modeled Wellbore Pressure on December 31, 2017 (psia)	Increase Over Original Pressure (psi)
WDW-157	2770.60	398.22
WDW-169	2760.74	388.36
WDW-249	2762.64	387.04
WDW-407	2772.50	400.12

Tables 5.1.3-V through 5.1.3-VIII list the predicted flowing and annual 24-hour shut-in pressures at the top of the Upper Frio injection interval sands in WDW-157, WDW-169, WDW-249 and WDW-407.

Figures 5.1.3-29 through 5.1.3-32 depict the decline in pressure at the wells for a one-year period following shut-in. The pressure at the wellbore will decline below the critical pressure within one day of shut-in.

The PredictW input and output results for 4 years of continuous injection (2 years at offset well followed by 2 years at the well in question), followed by a one-year shut-in, are presented in Appendix 5.1.3-7. Appendix 5.1.3-8 contains the PredictW input and output for the 24-hour annual shut-ins.

2015 Modeling

The rate schedule for the future operational period consisted of injection at Vopak and Texas Molecular at a rate of 450 gpm per facility (i.e., 900 gpm total) through December 2030. WDW-407 and WDW-422 become operational January 1, 2016 in the model. In order to maximize wellbore pressure, the entire 450 gpm for the facility was injected into the well being considered. For example, when determining the future wellbore pressure at Vopak's WDW-157 well, the rate into Vopak's WDW-407 was set at 0 gpm and WDW-157 was set at 450 gpm. The flow at the Texas Molecular site was evenly split (450 gpm/3 wells = 150 gpm). Tables 5.1.3-IX through 5.1.3-XIII list the future flowing wellbore pressure on a monthly basis and the 24-hr shut-in pressure on an annual basis for each well. Figures 5.1.3-33 through 5.1.3-37 show the pressure response at each wellbore during the operational life through December 2030. Figures 5.1.3-38 through 5.1.3-42 depict the anticipated post operational pressure decay during the year following shut-in. Appendix 5.1.3-9 contains the PredictW input and output for the additional runs considered in this submittal.

5.1.4 Cone of Influence

The critical pressure rise at this site is 230.22 psi at the top of the Upper Frio, and 248.48 psi at the top of the Lower Frio, as discussed in Section 3.7.5. Figures 5.1.4-1 and 5.1.4-2 depict isobaric contours of the rise in the Lower Frio reservoir pressure at the end of the operational life (December 31, 2017), considered in the 2007 modeling assuming an infinite acting reservoir, and a reservoir with a single-fault, respectively. The 248.48-psi contour is located at a maximum distance of 19600 feet from any of the wells at this site for the infinite acting reservoir case and 18600 feet for the single-fault reservoir case. Computer input and output from the PredictW program is presented in Appendices 5.1.4-1 and 5.1.4-2 for the Lower Frio Infinite acting and single fault reservoir cases. Figures 5.1.4-3 and 5.1.4-4 depict the maximum rise in the Upper Frio reservoir pressure for an infinite acting reservoir and a reservoir with a single fault. These two figures are a composite of the eight scenarios of 4 years of injection from any combination of wells. The 230.22 psi contour is located at a maximum distance of 1800 feet from any of the wells for the infinite acting reservoir case and 267 feet from any of the wells for the single fault reservoir case. PredictW input and output are contained in Appendices 5.1.4-3 and 5.1.4-4 for the Upper Frio infinite acting and single fault reservoir cases.

2015 Modeling Addition

The additional modeling conducted for this submittal considers faults with variable transmissiveness. Figure 5.1.4-5 depicts isobaric contours of the rise in pressure on December 31, 2030 in the Lower Frio for the case of non-transmissive faults. The

248.48 psi contour extends a maximum of 13,000 feet south of the Vopak and Texas Molecular wells. Figures 5.1.4-6 through 5.1.4-11 depict the isobaric contours for the 25%, 50%, 75%, 90%, 95% and 100% fault transmissiveness cases.

The PredictW input and output is contained in Appendix 5.1.4-5. Table 5.1.4-I summarizes the distances to the critical pressure contour from each facility. The greatest distance to the critical pressure rise shown in Table 5.1.4-I is the Lower Frio infinite acting case presented in the 2007 submittal. Comparison of the 2007 Infinite Acting case to the additional modeling case for 100% transmissive faults indicates the 2007 modeling run yielded a larger cone of influence in all directions. The 2007 Faulted Reservoir case also yielded a larger cone of influence than the 0% transmissive fault case presented in this submittal.

5.2 Plume Migration Modeling

The SWIFT code was employed to address lateral transport of waste. The purpose of the migration analysis is to define a "No-Migration" boundary for the site, which establishes a conservative representation of waste plume configuration after 10,000 years, considering combined regional background groundwater velocity and density drift effects.

2007 Modeling

A uniform grid block size of 300' x 300' was used for the SWIFT layout. The low-density and high-density plume runs utilized the identical geometry. The low-density plume runs utilized a SWIFT grid consisting of an array of 346 blocks in the X-direction and 161 blocks in the Y-direction. The X-direction was oriented updip. The high density plume runs utilized a 221 x 161 grid array. The X-direction was oriented downdip.

2015 Modeling Addition

Additional modeling runs (low density and high density injectate) were conducted on the Lower Frio which incorporated injection from all existing Class I and Class II wells within ten miles of the Vopak and Texas Molecular facilities. The low density and high density models were identical, except for the waste density being injected in the Vopak and Texas Molecular wells and the boundary pressures used to induce regional flow. The target regional flow was 0 feet per year for the low density model and 0.5 feet per year in the downdip (SSE) direction for the high density model. The SWIFT Model consisted of a grid 259 blocks in the X-direction and 273 blocks in the Y-direction. The blocks were 300 feet in the X and Y direction.

5.2.1 Parameter Review

The parameter values listed in Table 3.1-I were utilized to develop a scenario which would bound plume migration for the Lower and Upper Frio Sands.

The hydraulic conductivity was based on a permeability of 2500 md. The thicknesses used were 70 feet for the Lower Frio models and 50 feet for the Upper Frio models.

2007 Modeling

The block depths implemented in SWIFT were based on the estimated plume paths shown on the structure maps for the Lower Frio (Figure 2.1.5-2) and the Upper Frio (Figure 2.1.5-1). The elevations utilized in SWIFT varied only in the X-direction (parallel to migration direction).

2015 Modeling Addition

The block depths were determined by digitizing the Lower Frio structure map (Figure 2.1.5-2) and allowing Surfer® to generate depths for the SWIFT models.

5.2.2 Regional Flow Implementation and Stabilization

In order to enforce the desired regional flow (low-density plume: 0 ft/yr; high-density plume: 0.5 ft/yr), the updip and downdip plume models employed static perimeter pressures. The perimeter pressures were adjusted iteratively until an acceptable regional flow rate was obtained throughout the plume corridor in the SWIFT simulation grid. The regional flow for the low-density Lower Frio plume run was stabilized at 0.0±0.015 ft/yr. The flow field for the high-density Lower Frio plume run was stabilized to 0.5±0.015 ft/yr in the downdip direction. For the Upper Frio, the regional flow was stabilized at 0.0±0.015 ft/yr for the low-density plume and 0.5±0.015 ft/yr for the high density plume.

2007 Modeling

Figures 5.2.2-1 and 5.2.2-2 show the stabilized flow field for the Lower Frio low-density plume model, following 10,000 days and 10,000 years. Figures 5.2.2-3 and 5.2.2-4 show the stabilized flow field for the high-density Lower Frio plume model following 10,000 days and 200 years, respectively. A vector in each grid block represents the error in the model versus the target distance over 10,000 years. Since the velocity achieved was within 1.015 ft/yr of the target velocity, no vectors are visible. The SWIFT input and output data for the stabilization of the Lower Frio models are presented in Appendix 5.2.2-1 (low-density plume) and Appendix 5.2.2-2 (high-density plume).

Figures 5.2.2-5 and 5.2.2-6 show the stabilized flow field for the Upper Frio low-density plume model following 10,000 days and 200 years. Again, no vectors are visible since the velocity achieved was within 0.015 ft/yr of the target velocity. Appendix 5.2.2-3 contains the SWIFT input and output for this stabilization run. Figures 5.2.2-7 and 5.2.2-8 show the stabilized flow field for the Upper Frio high density plume model following 10,000 days and 200 years. Appendix 5.2.2-4 contains the SWIFT input and output for this stabilization run.

2015 Modeling Addition

Figures 5.2.2-9 and 5.2.2-10 show the stabilized flow field for the Lower Frio low-density plume model, which incorporates the structure, following 10,000 days and 10,000 years. Figures 5.2.2-11 and 5.2.2-12 show the stabilized flow field for the high-density Lower Frio plume model following 10,000 days and 200 years. The stabilized flow field for the low-density model exhibited an error of less than 1500 feet or 5 grid blocks. The stabilized flow field for the high-density model exhibited an error of less than 300 feet or 1 grid block. Appendices 5.2.2-5 and 5.2.2-6 contain the SWIFT input and output for these stabilization runs.

5.2.3 Operational Period

2007 Modeling

The operational period for the Lower Frio models consists of all historical volumes injected between December 1979 and December 31, 2006 in addition to anticipated injection between January 1, 2007 through December 31, 2017. The following table lists the historical and future injection into the Lower Frio:

Well	Start Date	End Date	Injection Volume (gallons)			Future Injection Rate, gpm
			Historical Through 12/31/06	Future Through 12/31/17	Total	
WDW-157	11/80	12/31/17	970,486,242	1,735,776,000	2,706,262,242	300
WDW-169	12/81	12/31/17	690,411,291	1,301,832,000	1,992,243,291	225
WDW-249	7/93	12/31/17	353,831,903	1,301,832,000	1,655,663,903	225
WDW-407	1/1/09	12/31/17	0	709,992,000	709,992,000	150
WDW-172	12/79	12/96	559,946,683	0	559,946,683	0
WDW-173	3/81	12/96	726,437,694	0	726,437,694	0
WDW-222	4/86	12/31/17	305,502,519	144,648,000	450,150,519	25
WDW-223	12/84	12/31/17	331,386,980	144,648,000	476,034,980	25
ID No. 110	3/02	8/06	77,158,788	0	77,158,788	0
ID No. 127	11/99	9/06	37,828,140	0	37,828,140	0
ID No. 139	2/05	12/31/17	20,267,982	327,264,000	347,531,982	58.33

The operational period for the Upper Frio models consists of historical injection into WDW-249 between November 1999 and October 2000 in addition to future injection between January 1, 2007, and December 31, 2017. The future injection will be limited to a net time period of 1460 days during the period between January 1, 2007 and December 31, 2017. The rate will be limited to an average of 175 gpm into the Upper Frio reservoir.

The injectate from WDW-157, WDW-169, WDW-249 and WDW-407 was assigned an initial concentration value, C_o, of unity (mass of solute per unit mass of fluid); computed concentration levels then refer to C/C_0. The offset injection wells were assigned a concentration of zero. Figure 5.2.3-1 illustrates the plume configuration in the Lower Frio Sand on December 31, 2017. The relative concentration of waste (C/C_0) remains at the maximum value of 1.0 from the wellbores to a distance of approximately 500 to 600 feet. The 7×10^{-11} concentration level is at a maximum distance of 12,000 feet from any of the wellbores. Figure 5.2.3-2 illustrates the plume configuration in the Upper Frio following four years of injection.

SWIFT input and output for the low-density and high-density plumes for both the Lower and Upper Frio is presented in Appendices 5.2.3-1 through 5.2.3-8. The following table provides details on the contents of these appendices:

		Low-density	High-density
Lower Frio	Historical Injection	Appendix 5.2.3-1	Appendix 5.2.3-3
	Future Injection	Appendix 5.2.3-2	Appendix 5.2.3-4
Upper Frio	Historical Injection	Appendix 5.2.3-5	Appendix 5.2.3-7
	Future Injection	Appendix 5.2.3-6	Appendix 5.2.3-8

2015 Modeling Addition

The operational period for the Lower Frio models consists of all historical volumes injected between June 1969 and December 2014 in addition to anticipated injection between January 2015 through December 2030. The following table lists the historical and future injection in to the Lower Frio:

Well	Start Date	End Date	Injection Volume (gallons)			Future Rate to 12/31/30 (gpm)
			Historical to 12/31/14	Future to 12/31/30	Total	
WDW-157	11/80	12/31/30	1,078,931,690	2,011,716,000	3,090,647,690	225
WDW-169	12/81	12/31/30	980,131,853	1,301,724,000	2,281,855,853	150
WDW-249	7/93	12/31/30	665,143,431	1,301,724,000	1,966,867,341	150
WDW-407	1/1/16	12/31/30	0	1,775,196,000	1,775,196,000	225
WDW-422	1/1/16	12/31/30	0	1,183,464,000	1,183,464,000	150
WDW-172	12/79	12/96	347,817,403	0	347,817,403	0
WDW-173	3/81	12/96	726,437,694	0	726,437,694	0
WDW-222	4/86	12/31/30	473,080,516	946,728,000	1,419,808,516	112.5
WDW-223	12/84	12/31/30	321,886,980	946,728,000	1,268,614,980	112.5
WDW-036	6/69	8/31/91	1,486,978,909	0	1,486,978,909	0
WDW-147	7/79	12/31/30	2,164,823,136	0	2,164,823,136	0
WDW-148	7/78	12/31/30	3,229,588,050	1,893,456,000	5,123,044,050	225
WDW-162	1/80	12/31/30	2,704,746,609	1,893,456,000	4,598,202,609	225
WDW-319	12/00	12/31/30	1,204,304,928	3,156,760,000	4,360,064,928	375
WDW-397	4/08	12/31/30	1,251,727,199	5,049,216,000	6,300,943,199	600
WDW-398	5/11	12/31/30	780,421,000	5,049,216,000	5,829,637,000	600
ID No. 110	3/02	5/13	78,862,980	0	78,862,980	0
ID No. 127	11/99	12/31/30	73,822,098	245,448,000	319,270,098	29.17
ID No. 139	2/05	12/31/30	122,530,088	490,896,000	613,426,086	58.33
ID No. 166	4/05	12/31/30	113,610,126	736,344,000	849,954,126	87.5

The injectate from the Vopak and Texas Molecular wells was assigned an initial concentration of unity. The offset injection wells were assigned a concentration of zero. Figure 5.2.3-3 illustrates the plume configuration in the Lower Frio Sand on December 31, 2030. The relative concentration of waste (C/C_0) remains at the maximum value of 1.0 from the wellbores to a distance of approximately 1000 to 1500 feet. The 7 x 10^{-11} concentration level is at a maximum distance of 14,500 feet from any of the wellbores.

The SWIFT input and output for this modeling addition are provided in the appendices listed in the following table:

		Low Density	High Density
Lower Frio	Historical Injection	Appendix 5.2.3-9	Appendix 5.2.3-11
(2015 Modeling Addition)	Future Injection	Appendix 5.2.3-10	Appendix 5.2.3-12

5.2.4 10,000-Year Plume Migration

5.2.4.1 Updip Migration of Low-Density Plume

2007 Modeling

The primary driving force in the low-density plume migration will be the difference in density between the injectate and the native reservoir brine. The regional flow was maintained at 0 ft/yr for the entire modeling run. Figure 5.2.4.1-1 depicts the Lower Frio low-density migration plume. Both the base case (α_L = 160 feet, α_T = 80 feet) and the sensitivity case (α_L = 160, α_T = 32) are shown. The maximum migration distance will be 54,000 feet updip from the site at a concentration reduction factor, C/C_0, of 7 x 10^{-11}, following 10,000 years. The maximum plume width was yielded by the sensitivity run. At a concentration reduction factor of 7 x 10^{-11}, the width will be 38,400 feet following 10,000 years. In addition, the effect of fluid withdrawal, as discussed in Section 3.7.3, is to move the plume 3669 feet in a direction of E 72.8° S. The maximum concentration inside the plume is 0.254, and occurs at an updip distance of 40,500 feet from the site. The SWIFT input and output for the Lower Frio low-density plume migration simulation are presented in Appendix 5.2.4-1.

Figure 5.2.4.1-2 depicts the Upper Frio low-density migration plume. The maximum migration distance will be 24,800 feet updip from the site at a concentration reduction factor of 7×10^{-11} following 10,000 years. The maximum width of the plume will be 22,600 feet. The SWIFT input and output for the Upper Frio low-density plume migration are presented in Appendix 5.2.4-2.

2015 Modeling Addition

Figure 5.2.4.1-3 depicts the Lower Frio low-density migration plume. The maximum migration distance is 54,800 feet from the site at a C/C_0 of 7×10^{-11}, following 10,000 years of migration. The maximum width of the plume is estimated to be 43,500 feet at a C/C_0 of 7×10^{-11}. The maximum concentration in the plume is 0.320 and occurs 21,500 feet from the site in a direction of N 30.5° W. The SWIFT input and output for the Lower Frio low-density plume migration are presented in Appendix 5.2.4-5. The effect of oil, gas, and water production from the Frio Formation is to induce movement in both the Lower Frio injection interval and the Upper and Middle Frio injection interval in the direction S2.8°W, as discussed in Section 3.7.3. Since the direction of this induced movement is opposite the updip direction of migration of the low-density plume, the effect of oil, gas, and water production on the updip extent of low-density plume migration is ignored. The southern boundaries of the low-density plumes were extended 5645 feet in the direction S2.8°W to overestimate the effect of production, as shown on Figures 2.1.5-1, 2.1.5-2, and 8.1-1.

5.2.4.2 Downdip Migration of High-Density Plume

The main factors affecting the high-density plume migration are the difference in density between the injectate and native reservoir brine and the downdip regional flow of 0.5 ft/yr. The migration period for the high density plume was limited to 200-years since the plume density is much higher than the density of the native reservoir brine.

2007 Modeling

Figure 5.2.4.2-1 depicts the Lower Frio high-density migration plume. The maximum migration distance at a concentration reduction factor, C/C_0, of 7 x 10^{-11} will be 17,200 feet from the site following 200 years. The maximum width of the plume will be 22,150 feet at a C/C_0 of 7 x 10^{-11}. The SWIFT input and output for the Lower Frio high-density plume migration are presented in Appendix 5.2.4-3.

Figure 5.2.4.2-2 depicts the Upper Frio high density migration plume. The maximum migration distance will be 8,300 feet downdip from the site at a concentration reduction factor of 7 x 10^{-11} following 200 years. The maximum width of the plume will be 11,200 feet. The SWIFT input and output for the Upper Frio high-density plume migration are presented in Appendix 5.2.4-4.

2015 Modeling Addition

Figure 5.2.4.2-3 depicts the Lower Frio high-density migration plume. The maximum migration distance at a C/C_0 of 7 x 10^{-11} will be 16,000 feet from the site following 200 years. The maximum width of the plume will be 26,500 feet at a C/C_0 of 7 x 10^{-11}. The maximum concentration inside the plume is 0.982 at a distance of 3850 due east of the facility. The SWIFT input and output are presented in Appendix 5.2.4-6. The effect of oil, gas, and water production from the Frio Formation is to induce movement in both the Lower Frio injection interval and the Upper and Middle Frio injection interval by 5645 feet in the direction S2.8°W, as discussed in Section 3.7.3. The southern boundaries of the high-density plumes were extended 5645 feet in the direction S2.8°W to overestimate the effect of production, as shown on Figures 2.1.5-1, 2.1.5-2, and 8.1-1.

5.3 Vertical Migration

In this section, vertical migration is estimated using analytical calculations. Section 5.3.1 presents migration in the matrix of the containment interval, while Section 5.3.2 presents migration up a hypothetical brine-filled wellbore.

5.3.1 Vertical Migration in the Containment Interval

Vertical migration in the containment interval is possible by two mechanisms. Advective transport is movement of injectate into the containment interval in response to pressurization of the injection interval. This is estimated in Section 5.3.1.1. Diffusion is based on the molecular motion of waste constituents. In Section 5.3.1.2, the highest diffusion coefficient of any of the petitioned waste constituents was used in combination with the lowest C/C_0. This provides the highest degree of conservatism to the diffusion estimate.

5.3.1.1 Vertical Advection

The following assumptions have been used to maximize the vertical migration due to advection in the vicinity of the injection wells.

1. The pressure adjacent to a well corresponds to the maximum flowing bottom-hole pressure increase predicted at the end of future injection, or 794.25 psi at the top of the Upper Frio injection interval (infinite acting reservoir) at the end of injection operations, from Section 5.1.3.
2. The natural downward gradient due to the pressure difference between the lowermost USDW and the injection interval is ignored. Using the pressure difference between the lowermost USDW and the injection interval would reduce the pressure difference used to calculate the vertical advection.
3. The maximum pressure is maintained throughout the operational period for 50.2 years (November 1980 through December 31, 2030), and 20 years into the falloff period after final shutin, a total of 70.2 years, or 25,627 days.

4. The pressure gradient caused by the maximum pressure is only applied across the first shale interval above the Upper Frio injection interval sand (at 5530 feet KB to 5550 feet KB at the injection site) across the entire containment interval. The shale layer is approximately 20 feet thick, as shown on Figure 2.2.1-1.
5. The vertical permeability in the shale is a conservatively high value of 0.0001 md. Shale permeability is discussed in Section 3.3.
6. The viscosity of the injectate is the minimum value of 0.4235 cp for the less dense injectate at 5500 feet or the approximate depth below ground to the top of the Upper Frio injection interval (Table 3.5.4-I).

Using the above conservative assumptions, a steady-state interstitial fluid velocity in the first shale interval can be calculated using the following form of Darcy's Law from Dake (1978, page 113):

$$q = -1.127 \times 10^{-3} \frac{kA}{\mu B_o} \frac{dp}{dl} \qquad \text{Equation 5.3.1.1-1}$$

where

q	=	volumetric flow rate (STB/day)
STB	=	stock-tank barrels
k	=	permeability (md)
A	=	flow cross-sectional area (ft^2)
μ	=	viscosity (cp)
B_o	=	formation volume factor (reservoir barrels/STB) = 1
dp	=	pressure change (psi)
dl	=	depth or distance change (ft)

The flow rate, v in ft/day, may be determined from Equation 5.3.1.1-1 by dividing both sides of the equation by the flow cross-sectional area, A. In addition, the factor 5.6146 ($feet^3$/STB) is introduced, as shown below:

$$v = \frac{q}{A} = (-1.127 \times 10^{-3})(5.6146) \frac{k}{\mu} \frac{dp}{dl}$$

The worst-case vertical migration distance due to pressure-driven vertical advection can be calculated by multiplying the volumetric flow rate, v, by the duration of the operational period plus the falloff period.

Using the assumptions provided in this section, and assuming that a negative flow rate corresponds to upward movement, the worst-case steady-state velocity from vertical advection is:

$$\begin{aligned} v &= (-1.127 \times 10^{-3})\,(5.6146)\,\frac{0.0001\ \text{md}}{(0.4235\ \text{cp})}\,\frac{794.25\ \text{psi}}{20\ \text{feet}} \\ &= -5.9 \times 10^{-5}\ \text{ft/day} \end{aligned}$$

The worst-case maximum vertical migration due to advection over 25,627 days (70.2 years) is 1.5 feet above the top of the injection interval.

5.3.1.2 Vertical Diffusion

The analytical solution for calculation of vertical migration due to diffusion effects during the 10,000-year, post-operational period can be written as (Carslaw and Jaeger, 1959):

$$\frac{C}{C_0} = \text{erfc}\left(\frac{z}{2(D^{*}t)^{1/2}}\right) \qquad \text{Equation 5.3.1.2-1}$$

where

- C = concentration at z
- C_0 = initial concentration
- Z = distance from the source to the health-based limit in the vertical direction
- t = time
- D^* = coefficient of diffusion, defined by Miller (1989) as:

$$D^* = GD_0 \qquad \text{Equation 5.3.1.2-2}$$

where

G = geometric correction factor

D_0 = free-water diffusion coefficient

The following assumptions were used in the calculation:

1. The injectate plume maintains its maximum concentration at the base of the containment interval for 10,000 years.
2. Retardation of the injectate does not occur. The injectate does not sorb or react with the formation matrix and ground water. Sorption and reaction would decrease the vertical migration distance.
3. Lateral diffusion does not occur. Lateral diffusion would decrease the vertical migration distance.
4. The greatest diffusion coefficient at the top of the Upper Frio injection interval determined in Section 3.7.4.2, for an organic constituent (formaldehyde, 1.471 ft^2/yr), is used.
5. The reduction in the coefficient of molecular diffusion due to dead-end pores, electrostatically bound water, and inter-layer water in clays is not accounted for in this analysis.
6. The geometric correction factor for diffusion in shale is a conservative value equal to the square of the shale porosity (Miller, 1989). For a conservative calculation of diffusion distance, the shale porosity is assumed to be equal to 0.30, the porosity of the Anahuac shale (Section 3.3).
7. The geometric correction factor for diffusion in sand is a conservative value for a consolidated sandstone, $G = \phi^{0.8}$ (Miller, 1989), where ϕ is the sand porosity. A conservatively high sand porosity for sands in the containment interval is 0.33.
8. The temperature reduction, as the diffusive front moves up the borehole, is ignored. The lower temperatures encountered higher in the borehole will reduce the free-water diffusivity and, therefore, the extent of diffusion.

For a heterogeneous system, the harmonic average of the geometric correction factors for diffusion in the various strata of the containment interval is used as the composite geometric correction factor for the system. For the sand-shale stratigraphic column of the containment interval, the harmonic average for the geometric correction factor is given as:

$$G = \frac{z_t}{\frac{z_{sh}}{G_{sh}} + \frac{z_s}{G_s}} \qquad \text{Equation 5.3.1.2-3}$$

where

z_t = the total thickness of the containment interval

z_{sh} = the total thickness of shale within the containment interval

z_s = the total thickness of sand within the containment interval

G_{sh} = the geometric correction factor for diffusion in shale

G_s = the geometric correction factor for diffusion in sand

The vertical diffusion above the top of the Upper Frio injection interval is calculated below. The Upper Frio is directly overlain by the Anahuac Formation. As shown on Figure 2.1.3-1 and discussed in Section 2.1.3, the Anahuac Formation is shale (the Anahuac Shale) that is up to 550 feet thick from the injection site and updip along the plume migration path to approximately 4.5 miles north of the injection site. Beyond 4.5 miles north of the site, a sandy layer develops over the Anahuac Shale. At 10 miles north of the injection site, for example in the Cabot Scott No. 1 well (Control No. 185), the Anahuac Shale layer is 220 feet thick, and the Anahuac confining interval is 785 feet thick. The total net shale thickness at Control No. 185 is 325 feet, and the total net sand thickness is 460 feet. G, the geometric correction factor for diffusion for the Anahuac confining interval is calculated to be 0.17.

For

z_t = 785 feet

z_{sh} = 325 feet

z_s = 460 feet

G_{sh} = 0.30^2

G_s = $0.33^{0.8}$

Substituting these values for sand and shale thickness and geometric correction factors, the geometric correction factor for diffusion for the containment interval is:

$$G = \frac{785}{\dfrac{325}{0.30^2} + \dfrac{460}{0.33^{0.8}}}$$

$$= 0.17$$

Substituting the parameters into Equations 5.3.1.2-1 and 5.3.1.2-2 yields:

$$7 \text{ x } 10^{-11} = \text{erfc}\left(\frac{z}{2[(0.17)(1.471 \text{ ft}^2/\text{yr})(10{,}000 \text{ yr})]^{1/2}}\right)$$

Equation 5.3.1.2-4

Simplifying the equation yields:

$$7 \text{ x } 10^{-11} = \text{erfc}\left(\frac{z}{100 \text{ feet}}\right)$$ Equation 5.3.1.2-5

Substituting a temporary variable A into the equation, where

$$A = \frac{z}{100}$$ Equation 5.3.1.2-6

yields:

$$7 \text{ x } 10^{-11} = \text{erfc}(A)$$ Equation 5.3.1.2-7

Solving the complementary error function for A results in:

$$A = 4.611 \qquad \text{Equation 5.3.1.2-8}$$

Finally, solving Equation 5.3.1.2-6 for z yields:

$$z = 4.611 \times 100 \text{ feet} \qquad \text{Equation 5.3.1.2-9}$$

or

$$z = 461 \text{ feet}$$

5.3.2 Vertical Migration in Abandoned Boreholes

Pressure modeling determined that there is no vertical migration in abandoned boreholes due to vertical advection. Vertical diffusion in abandoned boreholes drives the 7×10^{-11} C/C_0 contour for an organic compound 1061 feet. Therefore, the total vertical migration to the 7×10^{-11} concentration reduction factor is calculated as 1061 feet. This is insufficient to cause any waste to exit the injection zone, as the confining portion of the injection zone has a thickness of 1200 feet. Sections 5.3.2.1 and 5.3.2.2 discuss the calculation of the vertical migration in abandoned boreholes caused by advection and diffusion, respectively.

5.3.2.1 Vertical Advection

The pressurization analysis (Section 5.1) projects that the maximum distance the COI extends from the injection site wellbore is 19,600 feet. Section 8.3 demonstrates that all wells within the COI are properly plugged, or are filled with mud adequate to resist pressures during injection. Therefore, no driving force exists for vertical advection in abandoned boreholes.

5.3.2.2 Vertical Diffusion

The analytical solution for vertical diffusion is given in Equations 5.3.1.2-1 and 5.3.1.2-2. The following assumptions were used in the solution:

1. The borehole intersects the injectate plume and the plume maintains its maximum concentration throughout the 10,000-year period.

2. The casing degrades only in the injection interval and above the confining portion of the injection zone. The casing does not degrade or collapse in the borehole. This assures maximum vertical diffusion by not allowing lateral diffusion into the confining portion of the injection zone and by not reducing the tortuosity.
3. The borehole is filled with 9.0-lb/gal mud.
4. The geometric factor for diffusion is equal to the square of the porosity of the 9.0-lb/gal mud. The porosity of the mud is 95%. Thus, $G = \phi^2 = 0.90$ (Miller, 1989), where ϕ is porosity.
5. The free-water diffusivity for the hazardous waste constituents (Section 3.7.4.2) is 1.471 ft^2/yr at the top of the Upper Frio injection interval.
6. The minimum concentration reduction factor for hazardous waste compounds is 7×10^{-11}.
7. Retardation of the injectate does not occur. The injectate does not sorb or react with the casing and borehole fluid. Sorption and reaction would decrease the vertical diffusion.
8. The temperature reduction, as the diffusive front moves up the borehole, is ignored. The lower temperatures encountered higher in the borehole will reduce the free-water diffusivity and, therefore, the extent of diffusion.

Substituting these parameters into Equations 5.3.1.2-1 and 5.3.1.2-2 yields:

$$7 \times 10^{-11} = \mathrm{erfc}\left(\frac{z}{2[(0.90)(1.471\,\mathrm{ft}^2/\mathrm{yr})(10{,}000\ \mathrm{yr})]^{1/2}}\right)$$

Equation 5.3.2.2-1

Simplifying the equation yields:

$$7 \times 10^{-11} = \mathrm{erfc}\left(\frac{z}{230\ \mathrm{feet}}\right)$$

Equation 5.3.2.2-2

Substituting a temporary variable A into the equation, where:

$$A = \frac{z}{230 \text{ feet}}$$ Equation 5.3.2.2-3

yields

$$7 \times 10^{-11} = \text{erfc}(A)$$ Equation 5.3.2.2-4

Solving the complementary error function for A results in:

$$A = 4.611$$

Finally, solving for z yields the maximum vertical diffusion distance in an abandoned borehole, or 1098 feet.

$$z = (4.611)(230 \text{ feet})$$ Equation 5.3.2.2-5

or

$$z = 1061 \text{ feet}$$